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DEMONSTRATION OF A 100 GBIT/S (GBPS) SCALABLE OPTICAL MULTIPROCESSOR INTERCONNECT SYSTEM USING OPTICAL TIME DIVISION MULTIPLEXING

Princeton University

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APPROVED:

JAMES E. NICHTER
Project Engineer

FOR THE DIRECTOR:

ROBERT G. POLCE, Chief
Rome Operations Office
Sensors Directorate

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6. AUTHOR(S)
Paul R. Prucnal and Stephen R. Forrest

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Princeton University
Office of Research & Project Administration
New South Bldg, 5th Floor,
PO Box 36
Princeton New Jersey 08544

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13. ABSTRACT *(Maximum 200 Words)*
Theoretical and an experimental demonstration of an error free 100 Gbit/s optical time division multiplexing (ODM) broadcast star computer interconnect has been performed. A highly scalable novel node design provides rapid inter-channel switching capability on the order of the single channel bit period (1.6 ns). The scalability for optical multichannel networks and interconnects is an important design issue to accommodate an ever growing number of users. It is therefore important that the channel selector at each node should be scalable to a large number of channels. We performed an analysis of a 1024-channel TDM channel selector which can be rapidly reconfigured to access any channel in a high speed OTDM system. We demonstrated that optical TDM technology based on a rapid channel tuner and fast demultiplexer has the potential to enable the construction of high performance, highly scalable and high bandwidth interconnects with crosstalk requirement of –30dB. To unable DWDM-OTDM interfacing between our OTDM interconnect and DWDM Network we proposed and demonstrated an all-optical format converter. This converter is an all-optical interferometric device based on non linear Sagnac loop with a semiconductor optical amplifier (SOA) inside.

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Optical Time Division Multiplexing, OTDM, Switching, Optical Multichannel Networks, Semiconductor Optical Amplifier

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Introduction

Although optical fibers provide the enormous transmission bandwidth required by emerging broadband network and high-performance computing applications, full access to this bandwidth is currently limited by electronic bottlenecks. To fully utilize the bandwidth of the optical fiber, high-speed multiplexing and demultiplexing are required, as well as high-speed routing control and contention resolution in packet-switched systems. Whereas electronics is currently able to achieve speeds of only a few GHz, all optical approach can offer speeds in the THz regime, which is commensurate with the bandwidth of the fiber. Several key issues must be addressed to achieve ultra-high processing speeds in optical communications and computing systems. In the past years, under this support, we have investigated a all new device called a Terabit Optical Asymmetric Demultiplexer (TOAD) for ultra high-speed all-optical networking applications such as pulse sampling, stretching, and demultiplexing, which eliminates key bottlenecks in ultrafast optical systems - electronics.

This work was performed in close collaboration with the Rome Laboratories and the members of the Lightwave Communications Research Laboratory at Princeton University. We have made substantial progress, both experimentally and theoretically, in our investigations of ultrafast optical interconnects.

Summary of Performed Work

Theoretical and an experimental demonstration of an error free 100Gb/s optical time division multiplexing (OTDM) broadcast star computer interconnect has been performed. A highly scalable novel node design provides rapid inter-channel switching capability on the order of the single channel bit period (1.6 ns). The scalability for optical multichannel networks and interconnects is an important design issue to accommodate an ever growing number of users. It is therefore important that the channel selector at each node should be scalable to a large number of channels. We performed an analysis of a 1024-channel TDM channel selector which can be rapidly reconfigured to access any channel in a high speed OTDM system. We demonstrated that optical TDM technology based on a rapid channel tuner and fast demultiplexer has the potential to enable the construction of high-performance, highly scalable and high bandwidth interconnects with crosstalk requirement of -30dB. To unable DWDM-OTDM interfacing between our OTDM interconnect and DWDM Network we proposed and demonstrated an all-optical format converter. This converter is an all-optical interferometric device based on non linear Sagnac loop with a semiconductor optical amplifier (SOA) inside.

I. Demonstration of 100Gb/s optical time division multiplexing (OTDM) broadcast star computer interconnect is presented

Although lightwave technology is meeting the demand for point-to-point and long-haul transport of digital information, routing packets at the nodes of the network has typically been carried out using electronically switched backplane routers. The growing capacity on the Internet is placing an ever greater demand on electronic routing technologies. While WDM can support large aggregate traffic bandwidths, it is difficult to perform routing functions which may involve challenging techniques such as dense wavelength conversion. Additionally, present WDM laser and filter tuning techniques rely upon slow technologies which increase the channel access latency and reduce the effective network bandwidth.

Recent advances in optical time division multiplexing (OTDM) have proven this technology's capability to handle the switching and routing needs for future. Channel access in OTDM networks is achieved by using time slot tuners and all-optical demultiplexers. Timing precision of less than 1ps is required to tune, multiplex, and demultiplex individual channels within the OTDM frame.

The computer interconnect we constructed is based upon an OTDM broadcast star architecture. The high-level architecture and node design is shown in Fig. 1. Nodes transmit information at a slow data rate, B, by modulating picosecond optical pulses. By using a scalable time slot tuner, the pulse is appropriately delayed to correspond to the desired destination time slot. Data pulses from all nodes are multiplexed into a time frame with an aggregate bandwidth of NB, where N is the number of nodes in the network. The pulse spacing between adjacent channels is $(NB)^{-1}$ or typically less than 10ps to achieve 100+ Gb/s. Ultrafast all-optical demultiplexers like the TOAD are used to extract the desired channel from the high capacity OTDM frame at the node receivers. Nodes can select the received time slot by using a time slot tuner to align the clock with an incoming time slot within the frame for all-optical demultiplexing.

To perform the functionality of a router, addresses are mapped to specific time slots within the network. Routing is achieved by sending each bit of the packet in a unique time slot corresponding to its destination node. All nodes in the network are synchronized by splitting and amplifying the optical output of a single modelocked fiber laser. Packet routing is performed by rapidly changing the state of the time slot tuner to transmit into time slots corresponding to destination addresses on the network. Recently, several experimental demonstrations [1-3] have shown that OTDM can meet many of the demanding needs of a router and a multiprocessor interconnect system which include full connectivity, low latency, and high aggregate throughput, reliability, and scalability. We report the demonstration of a testbed for a bit-interleaved 100-Gb/s OTDM broadcast star architecture that was previously proposed [4]. Unique to our network is a highly scalable, novel node design.

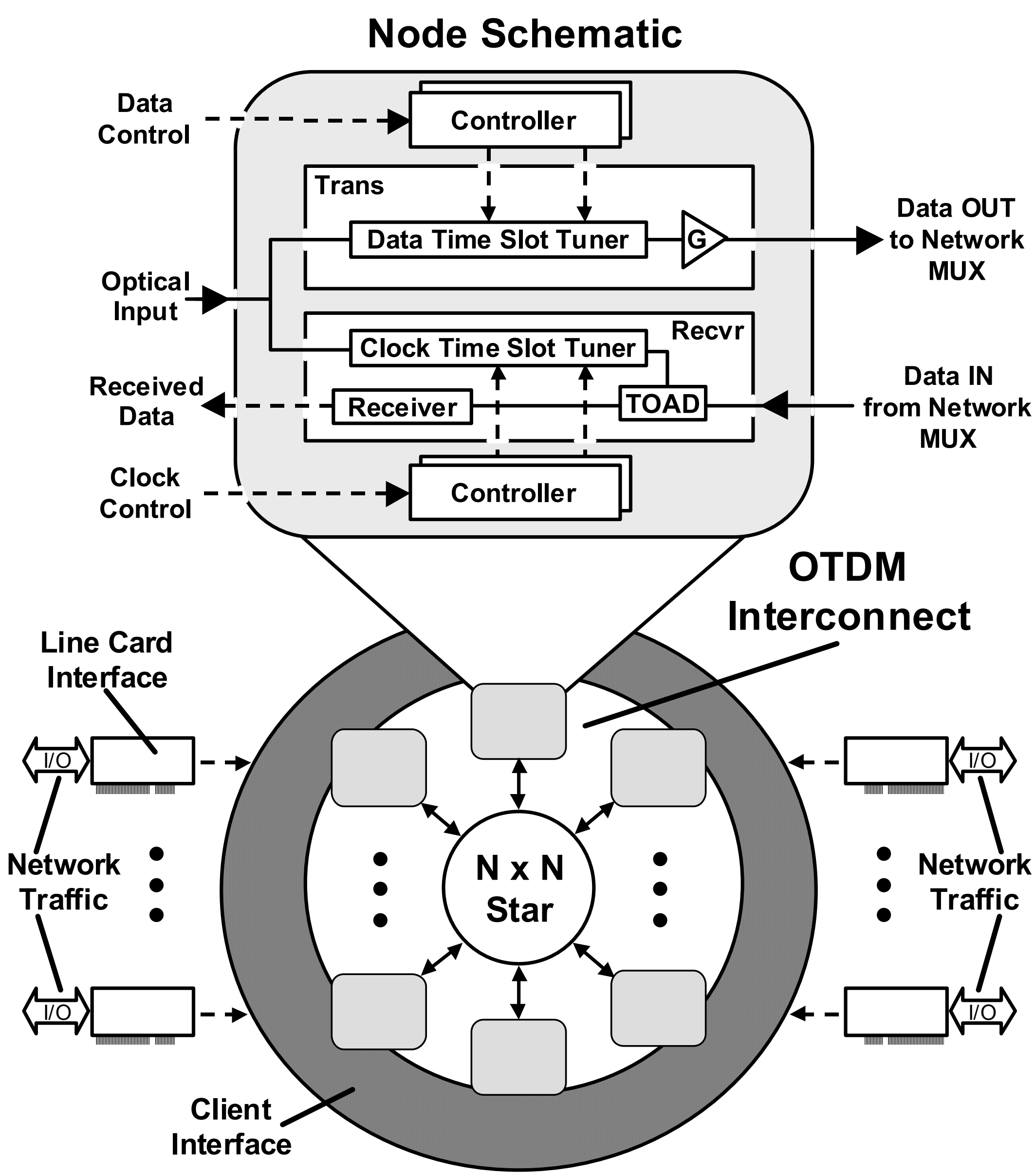

Figure 1. TDM router and node architecture

Figure 2 shows the network and novel node architecture experimental setup. The two key optical components of the node are the recently developed fast tunable delay line (FTDL) [5] and the terahertz optical asymmetric demultiplexer (TOAD) [6]. A controller card residing in a workstation sends electronic NRZ data at the single channel bit rate, B, and control bits to the driver board specially designed to control the two FTDLs on the clock and data fibers. The FTDLs consist of cascaded feed-forward Mach-Zehnder fiber delay lattices designed to produce optical copies of the incoming pulse stream organized into 2^k-bit subcells spaced by T with inter-subcell bit spacing [5]. The two modulators controlled by the driver board select one of the $2^k x 2^k$ (= N) time slots into which one of the copies is transmitted. The FTDLs in the node are used to transmit data into a selected time slot within the OTDM frame and align the clock with a given time slot for optical demultiplexing. Ultimately, the dimensionality of the network, N, is determined by k, the number of stages in the FTDL. The intermediate processing bandwidth, B' (= $1/T$), of the driver controller and the electro-optic modulators is designed to match the repetition rate of the picosecond pulsed fiber laser source and is related to the single channel bit rate as $B' = 2^k B$. Pulses are amplified by EDFAs and distributed to the individual nodes by 1xN splitters. After node data modulation and time slot selection, the data is multiplexed by precision fiber delays feeding an NxN star coupler. The high bandwidth OTDM frame is broadcast to all nodes in the network. Each node can demultiplex any single channel from the frame using an FTDL on the clock and a TOAD.

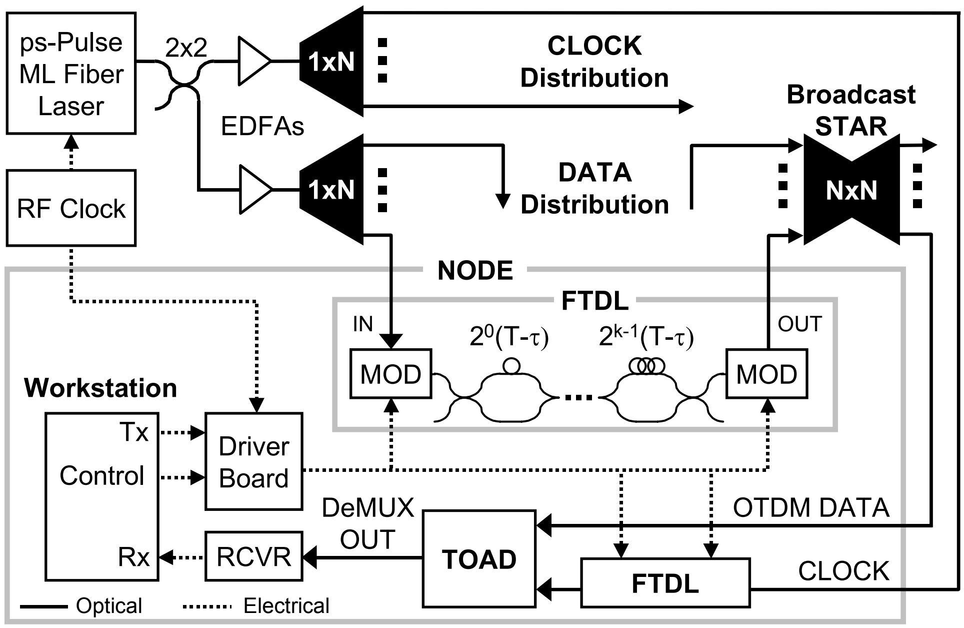

Figure 2. Experimental OTDM computer interconnect and node architecture

In our experimental testbed, we populated 16 (= N) time slots in the OTDM frame by constructing 2 (= k) stage FTDLs. The single channel data rate was chosen to match the OC-12 rate (B = *622.08 Mbit/s*). The 2-ps pulsed 1550-nm fiber laser repetition rate and intermediate electronic processing bandwidth were set to the OC-48 rate ($B' = 1/T = 2.48832$ *GHz*). The simple electronic design of the driver board permits the rapid control of the FTDL and provides low latency, arbitrary channel selection. The driver board was constructed using 4-bit electronic multiplexers (Vitesse) and simple logic operating at the OC-48 rate. To produce an OTDM frame with an aggregate bit rate of 100 Gb/s, $\tau = 10$ *ps* was chosen. Each TOAD was designed with a demultiplexing window width of about 10 ps at FWHM and a polarization splitter was used to separate data from clock at the output.

The 100-Gb/s multiplexing and demultiplexing experimental results are shown in Fig. 3. According to the design of the FTDL, the 16 time slots in our OTDM frame are arranged in 4 subcells each containing 4 time slots spaced by 10 ps. Our network demonstration focused on one of the subcells within the frame. Fig. 3a shows the aggregate eye diagram for a subcell with multiplexed data from 4 nodes with a fixed pattern, *1 – pseudorandom – 1 – 0*, on a bandwidth limited detector (34-GHz photodetector, 50-GHz oscilloscope). Upon demultiplexing by TOADs tuned to the individual channels, each is resolved in Fig. 3b (the 4th time slot is omitted as it is 0).

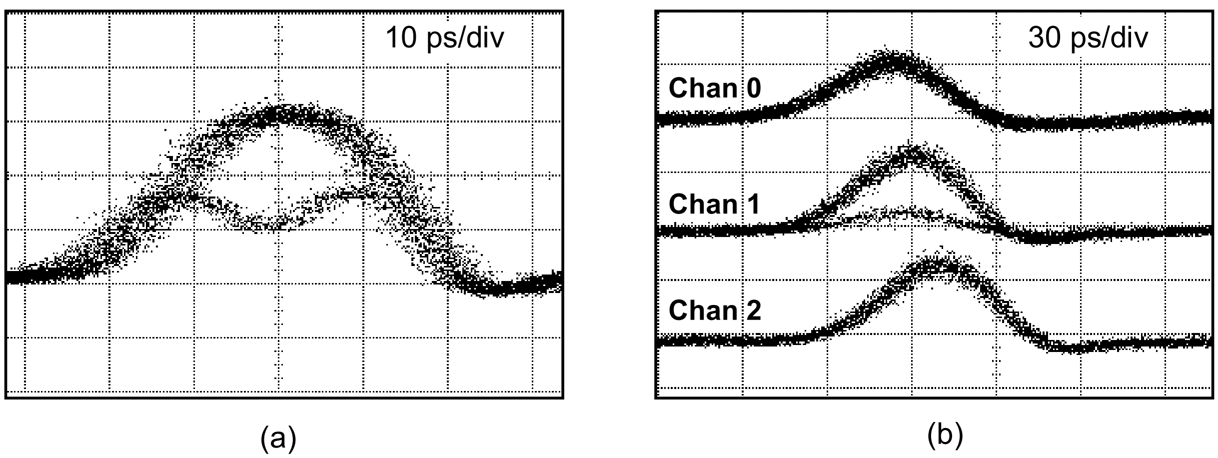

Figure 3 100 Gb/s multiplexed data OTDM subcell eye diagram on bandwidth limited detector, and demultiplexed TOAD output eye diagrams for three channels in subcell.

a) 100 Gb/s multiplexed data OTDM subcell eye diagram

b) Demultiplexed TOAD output eye diagrams

We constructed two fully functional nodes to measure the bit error rate (BER) and demonstrate the rapid inter-channel switching capability of the network nodes using an arbitration protocol. These experiments were performed using adjacent channels in the same 100-Gb/s subcell (Channels 0 and 1). Fig. 4a shows a plot of the BER versus the single channel average data input power at the TOAD when Chan 0 and Chan 1 were modulated with pseudorandom data. For average data and clock input powers greater than –21 dBm (13 fJ pulse energy) and -8 dBm (250 fJ pulse energy) respectively, several hours of error free operation have been achieved. Additionally, we have observed that the TOAD can provide gain to the demultiplexed signal. The inset to Fig. 4a shows the eye diagram of the data input (upper trace) and demultiplexed output (lower trace) of a TOAD demultiplexing a single channel of pseudorandom data with identical oscilloscope settings. The demultiplexed output is larger in amplitude than the input by approximately 6 dB.

The fast inter-channel switching capability of the network was also demonstrated by using a previously proposed, low latency arbitration protocol [4] and two nodes of the network. The receivers of both nodes are fixed to listen to their own time slots. Each node transmits its binary address at the single OC-12 channel rate into its own time slot. If successfully received, each node then transmits its address into the time slot of the other node. Fig. 4b shows a demonstration of the protocol using two nodes in the network whose time slots are adjacent in the 100-Gb/s subcell. The addresses assigned to Node 0 and Node 1 were 0101 and 0111 respectively. The traces shown are the demultiplexed TOAD outputs directly from the analog output of the receivers for the two nodes. After each node successfully receives its own address, the FTDLs rapidly reconfigure within a single bit period to transmit into the time slot of the other node. Note that each node now successfully receives the address of the other in its own time slot. The FTDLs and driver board electronics are capable of tuning to any one of the 16 time slots in the network within 1.6 ns, greatly reducing the hardware latency of the protocol.

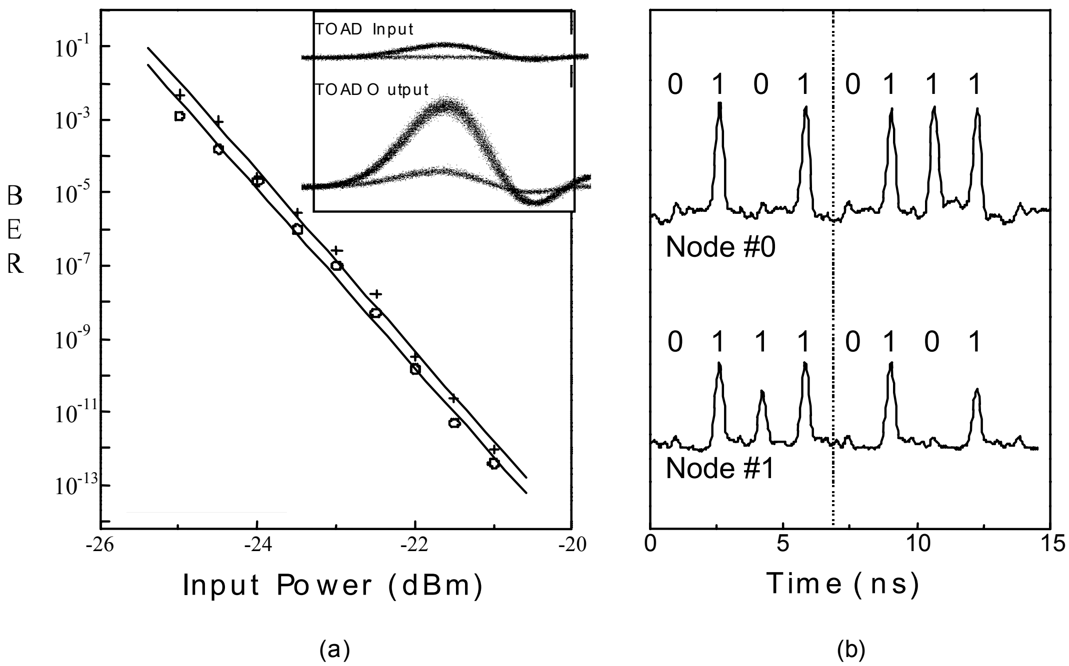

Figure 4 BER of channels 0 and 1 against average single channel input power, and demonstration of rapid channel selection on bandwidth limited analogue detector

a) BER of channels 0 and 1 against average single channel input power

Inset: TOAD input and output eye diagrams demonstrating gain

o *-channel 0*

+ *-channel 1*

b) Demonstration of rapid channel selection

In conclusion, we have demonstrated a fully connected 100-Gb/s OTDM network architecture that offers fast switching among data channels with reliable, error free operation and low latency. Since the active components of the FTDLs do not scale with the number of nodes [5], simply adding another stage, $k = 3$, (3 dB additional loss per node), scales the interconnect up to 64 (= N) nodes without taxing the power budget significantly. If OC-24 ($B = 1.24416$ GHz) is chosen as the single channel data rate and 10-GHz (= B') intermediate processing bandwidth electronics are used, an 80-Gb/s interconnect with a rapid inter-channel switching speed of 800 ps is feasible. In such a 64-processor architecture, coherent crosstalk does not limit the BER performance significantly [7]. Since the demultiplexer [8] and other optical components in the node can be integrated, we believe this network is practical for future, high-speed multiprocessor interconnect systems.

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II. All-Optical Format Converter

All-optical format conversion is a key operation which needs to be performed at the DWDM-OTDM interface. The newly proposed all-optical format converter is an all-optical interferometric device based on Sagnac loop with a semiconductor optical amplifier (SOA) inside. As indicated in Fig. 5, the SOA is displaced from the center of the loop. A tunable delay line is inserted in the loop to adjust the displacement Δx of the SOA from the center of the loop. A CW diode laser is connected to the input port of the Format Converter. The CW diode laser is tunable over a wide range from 1470nm to 1580nm with tuning accuracy of 0.01nm. The spectral width of the CW laser output is less than 1MHz. The incoming RZ data stream is obtained by modulating the output of a fiber laser, which generates pulses at full width at half maximum (FWHM) of 1.3ps. To simulate a weak channel signal in real networks, an EDFA was

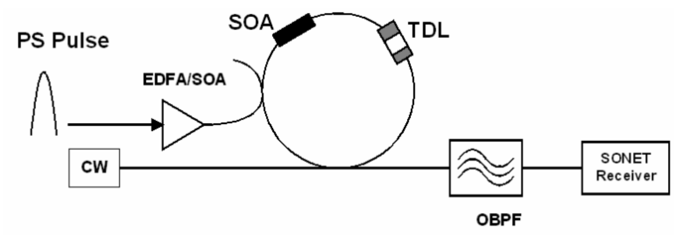

Figure 5 Experimental setup

used to amplify the RZ data stream. The output of the amplified RZ signal was fed into the control port of Format Converter through a 90:10 coupler, thereby coupling 10 percent of the incoming RZ data into the loop. The center wavelength of the RZ pulses is 1548nm, and its 3dB spectral width is 2.2nm. When the CW light enters the Format Converter, the light is split into two halves that travel in clockwise and counter-clockwise directions. In the presence of an ``0" in the RZ data stream, no control light enters the Format Converter in this particular bit period, and the CW light in both directions experience the same gain and phase change inside the loop. With the two counterpropagating CW lights experiencing the same phase delay in the loop, the two halves interferes at the 3dB coupler to exit at the input port. When there is a "1" in the RZ data stream, the picosecond pulse saturates the SOA. An optical band pass filter (OBPF) that only passes the CW light blocks the remaining pulse at the output port. Since the SOA is displaced to the left from the center of loop, there is a portion of the CW light that just passes the SOA in the clockwise direction before arrival of the “1" control pulse. The same portion of the CW light (split at the same time at the 3dB coupler) traveling in the counter-clockwise direction has not yet arrived at the SOA. It will arrive reach the SOA 2Δx /V later. Here, V is the group velocity of light in the fiber. The arrival of the “1" creates phase and gain changes for a portion of the counter clockwise CW light that extends 2Δx/V in time. That portion is switched out at the output port of the format converter due to the difference in phase experienced by itself and the clockwise propagating CW light.

The width of the switching window is linearly proportional to the displacement Δx as proven by experimental results shown in Figs. 6 (a), (b). The setup can stretch the picosecond pulse stream into a much broader stream optimally suitable for transmission between two nodes of a given fiber optic network. Fig. 6(a) shows a collection of the switching windows obtained through pump-probe scans. The switching windows were obtained by replacing the CW source with a picosecond pulse and using a retro-reflecting mirror in the control pulse path to facilitate relative time delay. In Fig. 6(b), FWHM of the switching windows are plotted versus the setting of the tunable delay line (TDL). Notice that the switching windows do not drop all the way down to zero even when Δx is approaching ``0" because of the finite length of the SOA and finite width of the RZ pulse. With 1.3ps RZ pulses and a 500nm SOA, the smallest switching window we obtained is 4ps. The widest switching window obtained is 58ps. With our setup, we can stretch 1.3ps

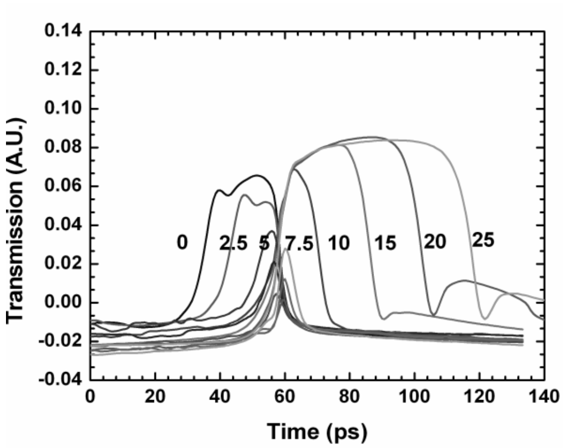

Figure 6a) Obtained results.

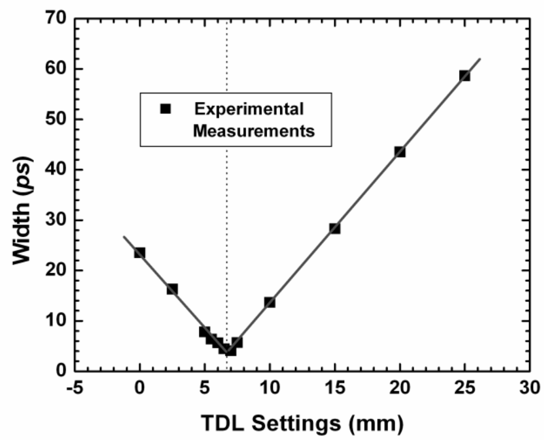

Figure 6b). Obtained results.

pulses to any value between 4ps to 58ps. This means that, for bit rates above 20Gb/s, we can convert RZ formatted data into NRZ formatted data. For bit rates lower than 20Gb/s, the setup provides a powerful tool to manage pulse width. Bit error rates **(**BER**)** lower than 10^{11} have been obtained as shown in Figure 7 by varying the average power of the control pulses (□) and CW inputs (◊). The BER were measured with the setup illustrated in Fig.7 with an OC-48 2^{31}-1 pseudo-random bit sequence (PRBS).

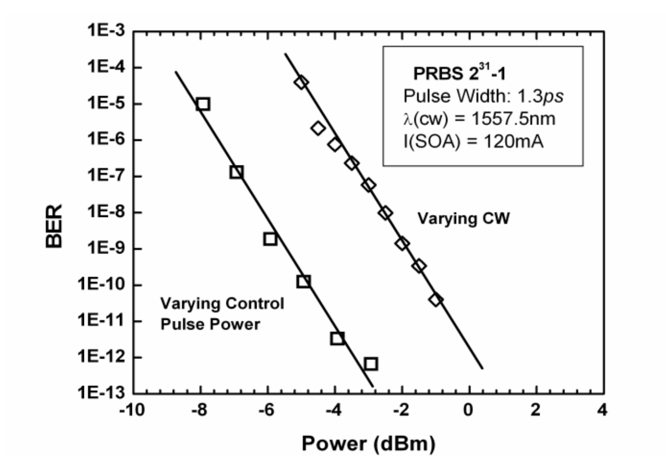

Figure 7 BER measurements

III. Crosstalk analysis in 1024-channel rapidly reconfigurable OTDM Interconnect

The scalability for optical multichannel networks and interconnects is an important design issue to accommodate an ever growing number of users. It is therefore important that the channel selector at each node should be scalable to a large number of channels. However, the accumulation of interferometric crosstalk from each node may impose a strict constraint on the size of such system [1].

We performed an analysis of a 1024-channel TDM tuner which can be rapidly reconfigured to access any channel in a 50-Gb/s OTDM system [2]. The OTDM tuner consists of a passive feed-forward delay lattice of k stages and two modulators at the input and output of the delay (see Fig. 8). The differential time delays at the *ith* lattice is $(2^{i-1})(T-\tau)$, where T^{1} is the period of the optical clock and τ^{-1} is the aggregate data rate. The output TDM time frame can be divided into 2^k sub cells, each of which consists of 2^k time slots. In total, as many as $2^k x 2^k$ TDM channels are available at the output, showing the excellent scalability of the device. Tuning of the device can be achieved by selecting control signal (m,n) at the input and output modulators respectively. The control signal (m,n) represents the state where the input modulator selects m^{th} bit from incoming optical clock and output modulator selects n^{th} sub-cell at the output. Demonstration of tuning among 256 channels (k=4) by varying control signal (m,n) are shown in Fig. 8(b) and (c).

Figure 9 outline an optical interconnect system based on this optical TDM tuner. The performance of the system[3] is equivalent to fully connected crossbar switches with low latency and aggregate bandwidth of several hundred Gb/s.

To scale the system size, the issue of crosstalk must be addressed. For a specific channel (m,n), the possible crosstalk contributed from other channels (assuming all ones) can be written as: $\delta_{m,n} = \sum_{\substack{i=1 \\ i \neq m}}^{K} (\delta_{in})_i + \sum_{\substack{j=1 \\ i \neq n}}^{K} (\delta_{out})_j$ where $K=2^k$, δ_{in} is the crosstalk for input modulators and δ_{out} for output modulators. Assuming equal crosstalk δ for all modulators, the total contribution can be written as $\delta_{m,n}= 2(K-1)\delta$. Notice the number of contributing components scales linearly with K , instead of KxK.

At the receiver, a statistical model is used [4] to calculate the probability p when the interferometric crosstalk causes unacceptable performance and determine the crosstalk requirement. Using E/O modulators with $\delta = -30$dB, 1000 nodes can be achieved with the failure rate less than 10^{-9}, corresponding to 32ms per year. Using a TOAD device as the optical demultiplexer[5].

In conclusion, optical TDM technology based on a rapid channel tuner and fast demultiplexer has the potential to enable the construction of high-performance, highly scalable and high bandwidth interconnects with crosstalk requirement of -30dB.

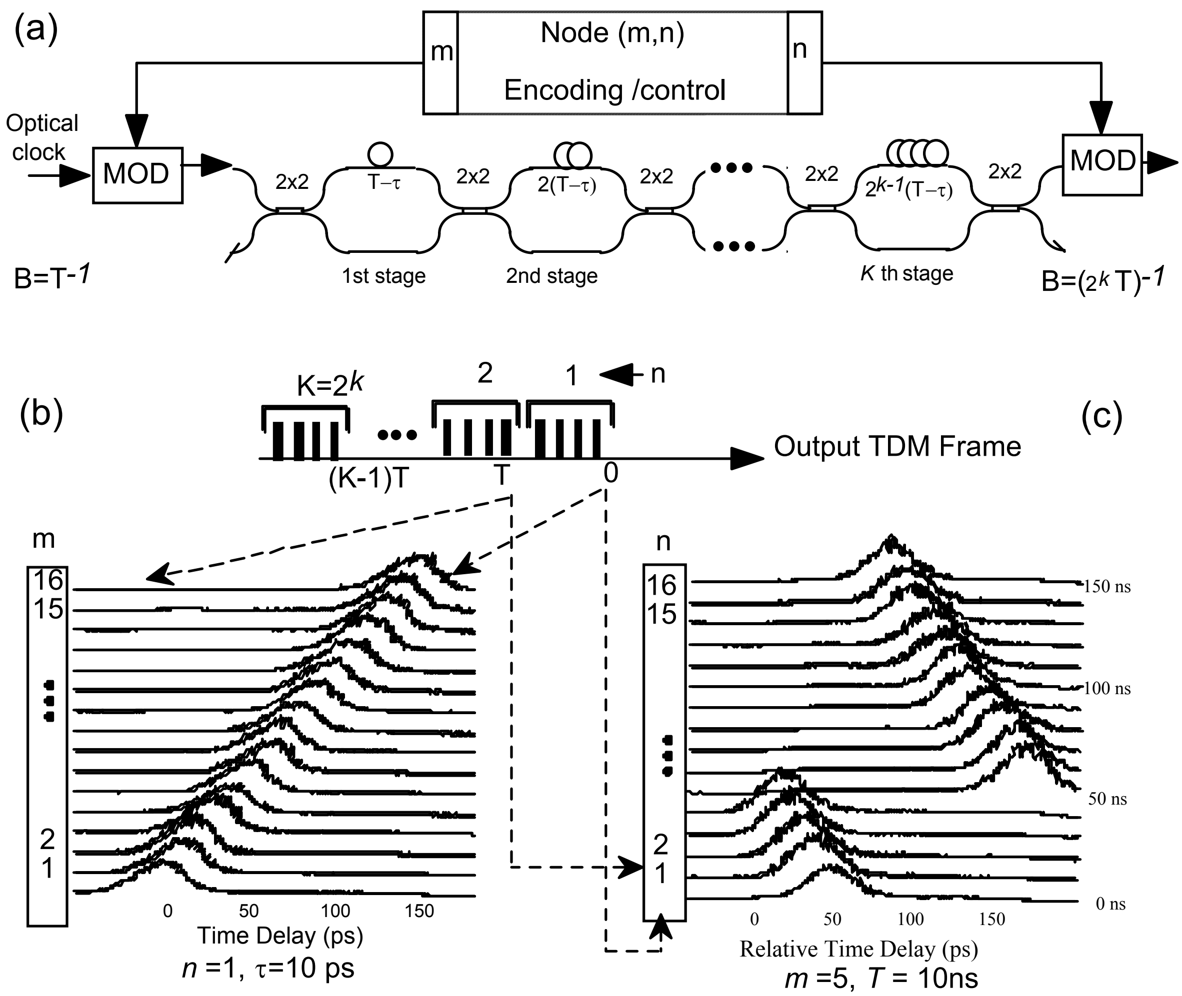

Figure 8a) Schematic of the optical TDM tuner. Demonstrations of tuning in a 4-stage delay lattice are shown in (b) fine tuning of 16 channels (k=4, τ=*10ps*) within first sub cell (n=1) by varying m and (c) tuning among different sub cells with T=10 ns by varying n at the output.

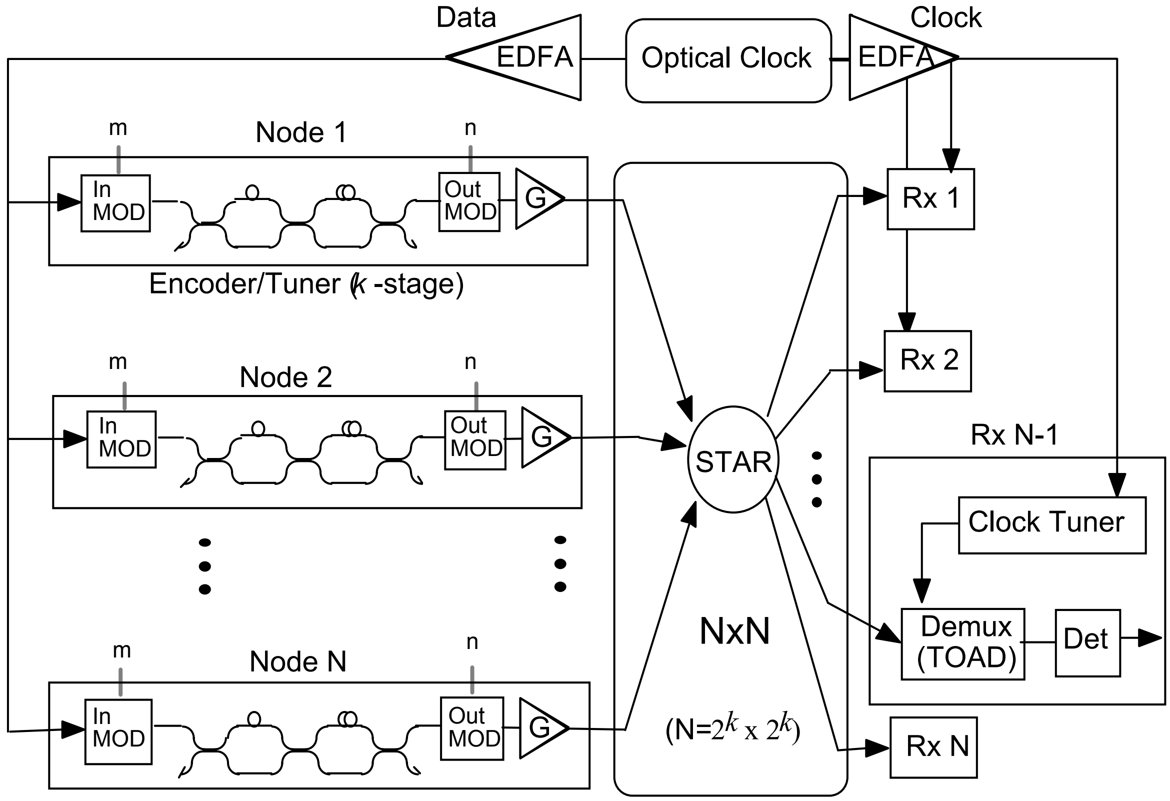

Figure 9 Schematic representation of an optical TDM interconnect based on the broadcasting star architecture.

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Summary of obtained results

1) Demonstration of a highly scalable, rapidly-reconfigurable, multicasting-capable, 100-Gb/s photonic switched interconnect based upon OTDM technology

2) Demonstration of Multicasting in a 100-Gb/s OTDM Switched Interconnect

3) Comparison of three nonlinear interferometric optical switch geometries for ultrafast all optical switching applications

4) In collaboration with SUN Microsystems Experimental Demonstration of Highly Scalable Computer Controlled Time Slot Tuner with Picosecond Resolution

5) Analysis of the Influence of a Crosstalk on the Scalability of Large OTDM Interconnects Using a Novel Rapidly-Reconfigurable, Highly-Scalable Time-Slot Tuner

6) Demonstration of an Integrated, Asymmetric twin-waveguide ultrafast all-optical switch

7) A novel wavelength and format converter using a terahertz optical asymmetric demultiplexer

8) Demonstration of all-optical format converter capable of ultra high speed operation

Published results

Journal Publications

1. K. -L. Deng, R. J. Runser, P. Toliver, I. Glesk, and P. R. Prucnal, “A highly scalable, rapidly-reconfigurable, multicasting-capable, 100-Gb/s photonic switched interconnect based upon OTDM technology,” Special Issue on Optical Network*s* in *Journal of Lightwave Technology* **18** (12) 1892 (2000).

2. I. Glesk, J. Runser, Kung-Li Deng, and P. R. Prucnal, "100 Gb/s Computer Optical Interconnect," Acta Physica Slovaca **50** (2) 229-234 (2000).

3. K.-L. Deng, R. J. Runser, I. Glesk, and P. R. Pru*cnal,* “Demonstration of Multicasting in a 100-Gb/s OTDM Switched Interconnect,” IEEE Photonics Technology Letters **12**, No. 5, 558-560 (2000) .

4. P. Toliver, R. J. Runser, I. Glesk, and P. R. Prucnal, “Comparison of three nonlinear interferometric optical switch geometries,” Optics Communication*s* **175** (4-6) 365-373 (2000).

5. R. J. Runser, K.-L. Deng, P. Toliver, I. Glesk, and P. R. Prucnal, “A Highly Scalable Router Using a Computer Controlled Time Slot Tuner with Picosecond Resolution”, Electronics Letters **35**, 1097 (1999).

6. I. Glesk, Kung-Li Deng and P. R. Prucnal, "Devices for Terabit Optical Networks, an Overview and Trends," Acta Physica Slovaca **49**: (3) 399-408 (1999).

7. K.-L. Deng, R. J. Runser, P. Toliver, C. Coldwell, D. Zhou, I. Glesk, and P. R. Prucnal, “Demonstration of a highly scalable 100-Gbs OTDM computer interconnect with rapid inter-channel switching capability”, Electronics Letters **34**, 2418 (1999).

8. D. Zhou, K. I. Kang, I. Glesk, and P. R. Prucnal, "An Analysis on Signal-to-Noise Ratio and Design Parameters of a Terahertz Optical Asymmetric Demultiplexer," Journal of Lightwave Technology **17**, 298 (1999).

9. K. -L. Deng, I. Glesk, K. I. Kang, and P. R. Prucnal, "Influence of Crosstalk on the Scalability of Large OTDM Interconnects Using a Novel Rapidly-Reconfigurable, Highly-Scalable Time-Slot Tuner", IEEE Photonics Technology Letters **10**, 1039 (1998).

10. D. Zhou, P. R. Prucnal, and I. Glesk, "A Widely Tunable Narrow Linewidth Semiconductor Fiber Ring Laser," IEEE Photonics Technology Letters, IEEE Photonics Technology Letters **10**, 781 (1998).

Conference Proceedings

1. P. V. Studenkov, M. R. Gokhale, J. Wei, W. C. Lin, I. Glesk,, P. R. Prucnal, and S. R. Forrest, “Integrated, Asymmetric twin-waveguide ultrafast all-optical switch,” IEEE/LEOS’00, paper WCC4, pp. 645-646, Rio Grande, Puerto Rico, 13-16 November 2000.

2. B. Wang, I. Glesk, and P. R. Prucnal, “Tunable Parallel Optical Delay Line,” IEEE/LEOS’00, paper WZ3, pp. 621-622, Rio Grande, Puerto Rico, 13-16 November 2000.

3. R. J. Runser, I. Glesk, and P. R. Prucnal, “Experimental Demonstration of a 1.5 ps Demultiplexing Window for High Speed Optical Networks Using a Forward-Pumped Mach Zehnder TOAD”, CISS2000, *Proceedings of 34th Annual Conference on Information Sciences and Systems*, Princeton University, NJ, March 15-17, 2000

4. D. Zhou, I. Glesk and P. R. Prucnal, “A novel optical pulse width management device,” in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, Washington DC, 2000), pp. 133.

5. P. Toliver, R. J. Runser, I. Glesk, and P. R. Prucnal, “Comparison of Three Nonlinear Optical Switch Geometries,” in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, Washington DC, 2000), pp. 254-255.

6. D. Zhou, B. C. Wang, R. J. Runser, I. Glesk, and P. R. Prucnal, “A novel wavelength and format converter using a terahertz optical asymmetric demultiplexer,” *OSA Annual Meeting/ILS-XV*, *September 26—October 1, 1999,* Santa Clara, California.

7. K.-L. Deng, R. J. Runser, I. Glesk, and P. R. Prucnal, “Demonstration of multicasting capability in a 100-Gb/s OTDM switched interconnect,” *LEOS '99,* paper WX2, pp. 591-592 San Francisco, CA, November 8-11, 1999.

8. I. Glesk, R. J. Runser, K.-L. Deng, and P. R. Prucnal “100 Gb/s optical computer interconnect,” *ECS '99*, 2nd Electronic Circuits and Systems Conference, Bratislava, 1999.

9. D. Zhou, B. Wang, R. Runser, I. Glesk, and P. Prucnal, “A Novel Wavelength and Format Converter Using a Terahertz Optical Asymmetric Demultiplexer,” *OSA Annual Meeting*, Paper TuV3, San Francisco, CA, September 28, 1999

10. P. Toliver, I. Glesk, and P. R. Prucnal, “Demonstration of 16-channel Multiple-Access Analog Optical TDM with 10-ps Channel Spacing”, in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, Washington DC, 1999), pp. 327-328

11. R. J. Runser, K.-L. Deng, P. Toliver, I. Glesk, and P. R. Prucnal, “Highly Scalable Optical TDM Router Using a Computer Controlled Time Slot Selector with Picosecond Resolution,” in *Photonics in Switching,* OSA Technical Digest (Optical Society of America, Washington DC, 1999), pp. 64/ThA3-1- ThA3-3/66.

12. D. Zhou, I. Glesk, and P. R. Prucnal, “Optical Impulse Response of Semiconductor Optical Amplifiers in a Counter-Propagation Mach-Zehnder Switch,” in *Photonics in Switching,* OSA Technical Digest (Optical Society of America, Washington DC, 1999), pp. 100/ThD3-1- ThD3-3/102.

13. K.-L. Deng, R. J. Runser, P. Toliver, C. Coldwell, D. Zhou, I. Glesk, and P. R. Prucnal, “Demonstration of a Highly Scalable 100-Gbs OTDM Computer Interconnect with Rapid Inter-channel Switching Capability,” in *Optical Fiber Communication Conference and the International Conference on Integrated Optics and Optical Fiber Communication,* OSA Technical Digest (Optical Society of America, Washington DC, 1999), pp. ThM2-1/165 - ThM2-3/167.

14. K.-L. Deng, I. Glesk, P. R. Prucnal and K. I. Kang, “Noise-immune Statistical cross-correlation technique for precision timing measurement using mode-locked fiber laser pulses”, in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, Washington DC, 1999)

15. P. R. Prucnal, I. Glesk, P. Toliver, R. Runser, and K.-Li Den, "Signal Processing in High Speed Optical Networks", ECOC-98, Madrid, Spain, September 21-25, 1998. Invited paper

16. K. -L. Deng, K. I. Kang, I. Glesk, and P. R. Prucnal, "Influence of Crosstalk on the Scalability of Large OTDM Interconnects Using a Novel Fast Time-Slot Tuner", in *Conference on Lasers and Electro-Optics,* Vol. 6, 1998 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1998), p. 4

Acronyms

AFRL	Air Force Research Laboratory
B	single channel bit rate
BER	bit error rate
CW	continuous wave
DARPA	Defense Advanced Research Projects Agency
dB	decibel, unit expressing the ratio between two amounts, for power dB = 10 $\log_{10} (P_1/P_2)$
dBm	measure of power defined as dBm =10 $\log_{10} \frac{\text{Power (milliwatts)}}{\text{1 milliwatt}}$
DWDM	dense wavelength division multiplex
E/O	electro-optic
EDFA	Erbium Doped Fiber Amplifier
fJ	femtojoule ($1x10^{-15}$ joule [unit of energy])
FTDL	fast tunable delay line
FWHM	full width at half maximum
Gb/s	gigabit per second ($1x10^{9}$ bits per second)
GHz	gigahertz ($1x10^{9}$ hertz)
k	number of stages in the FTDL
MHz	Megahertz ($1x10^{6}$ hertz)
mm	millimeter ($1x10^{-3}$ meter)
ms	millisecond ($1x10^{-3}$ second)
nm	nanometer ($1x10^{-9}$ meter)
N	number of nodes in the network
NRZ	non-return to zero
ns	nanosecond ($1x10^{-9}$ second)
OBPF	optical band pass filter
OTDM	optical time division multiplexing
PRBS	pseudo-random bit sequence
ps	picosecond ($1x10^{-12}$ second)
RZ	return to zero
SOA	semiconductor optical amplifier
T	inter-subcell bit spacing
TDL	tunable delay line
TDM	time division multiplex
THz	terahertz ($1x10^{12}$ hertz)
TOAD	Terabit Optical Asymmetric Demultiplexer
V	group velocity of light in the fiber
WDM	wavelength division multiplex
τ	demultiplexing window width
Δx	displacement of the SOA from the center of the loop
δ	crosstalk